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RESEARCH PAPER

Stand Density Management Diagrams for Three Exotic Tree Species in Smallholder Plantations in Vietnam

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Abstract When smallholder farmers establish tree plantations to sell wood to the wood industry, they may run into problems when the plantations are mature and to be marketed because these farmers usually (1) do not know how to estimate the growing stock and (2) do not have sufficient knowledge of the wood markets. In this study, we tackle problem (1) and present stand density management diagrams (SDMDs) as a simple tool that allows rapid estimation of standing volume from data that stem from very basic inventory. Our data come from smallholder plantations in Vietnam, from four communes in the provinces of Binh Dinh and Phu Tho. Immense afforestation activities have been taken place in the country during the past two decades and it is special to Vietnam that a large share of these afforestations are under smallholder management with the goal to generate an additional source of income for these rural poor. A certain type of SDMDs is elaborated for three important exotic tree species commonly used for establishing industrial tree plantations (*Acacia hybrid*, *Acacia mangium* and *Eucalyptus urophylla*). They can be used for volume estimation and are also a tool to guide stand management and

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silvicultural treatments in general. Both implementation of the inventory and usage of the SDMDs are straightforward and simple so that this tool may be well suited to support smallholders in a better informed marketing of their wood, as well as, a better informed silvicultural management of their plantations.

Keywords Smallholder plantations · Vietnam · Stand density management diagram · *Acacia mangium* · *Acacia hybrid* · *Eucalyptus urophylla*

Introduction

Smallholder Plantations in Vietnam

According to FAO (2010), the area of planted forests[1] increased for the period between 2000 and 2010 worldwide with an estimated positive annual change rate of 2.1%, which corresponds to an annual increase of 5 Mha of newly established plantations. In total it is estimated that 6.6% or 264 Mha of the world's forests are planted forests.

In Vietnam, similar patterns can be observed: after decades of forest loss—in the late 1960s forest cover was estimated to be 55% compared to only 17% in the late 1980s (De Koninck 1999)—a positive annual change rate of 1.6% was reported for the period from 2000 to 2010 (FAO 2010) so that the country is among the global top ten with the largest net gain in forest area. The annual growth in area of productive plantations is with 5.5% even higher (FAO 2010). Following official statistics, the total forest area in Vietnam in 2010 was 13.797 Mha or 44% of the country's land area. As cited in Clement et al. (2009), the Deputy Prime Minister of the Socialist Republic of Vietnam concluded in 2005 that this remarkable achievement is a result of land reforms and afforestation programmes initiated by the government in the early 1990s, in order to pursue economic, environmental, and social objectives (MARD 2007). These reforms comprised the following political, economic, and legal changes related to the forestry sector: (1) land classification and rules for forest protection; (2) allocation of land use rights; (3) recognition of communities as legal recipients for forest land use rights; (4) afforestation programmes (Programmes 327, 556 and 5MHRP); and (5) reform of state forest enterprises (Clement and Amezaga 2009).

Despite the success in restoring forest cover after decades of deforestation, there are also critical voices questioning official statistics and the impact of government led programmes on livelihood improvement and on smallholder's decisions regarding establishing plantation forest. Forest cover figures, for example, vary considerable depending on whether deforestation or reforestation processes are being stressed (Sunderlin and Huynh 2005), and should thus be interpreted with caution. In a study in Hoa Binh province, Clement et al. (2009) found government

[1] "Planted forests are composed of trees established through planting and/or through deliberate seeding of native or introduced species. Establishment is either through afforestation on land that until then was not classified as forest, or by reforestation of land classified as forest, for instance after a fire or a storm or following clearfelling" (FAO 2010).

statistics of forest cover change to be two to tenfold higher compared to the range of own estimates. Other studies suggest that Vietnam's deforestation is exported to neighbouring countries; e.g. the amount of timber imported increased and large quantities of illegal logs entered the country mainly from Laos and Cambodia (Meyfroidt and Lambin 2009). Also the goal of poverty alleviation was shown to be influenced lesser by forest land allocation than expected (Sikor and Nguyen 2007; Nguyen et al. 2008; Clement and Amezaga 2009); varying with local conditions. Further on, several studies showed that afforestation is not farmers' direct response to government led programmes and devolution of land use rights (Sikor 2001; Castella et al. 2006; Clement and Amezaga 2008; Meyfroidt and Lambin 2008; Clement et al. 2009); instead it is driven mainly by agricultural intensification, that is: concentration of agriculture on most suitable lands. On the other hand, there are also success stories which are specific to local conditions (see Sunderlin and Huynh 2005 for further reading).

According to MARD (2007), 20% of the forestry land[2] was allocated to households by March 2006, where local variations are high: for example, the figures for four provinces in the north-west of Vietnam vary in a range of 17.5–74.9% (Clement and Amezaga 2009), while in Dak Lak province in the Central Highlands only 0.8% are under household management (Nguyen et al. 2008). Characteristic is that the state is still dominant and that local people usually manage poor quality forests with emphasis on fast growing (exotic) tree species (Nguyen et al. 2008; Clement and Amezaga 2009).

Smallholders involved in farm forestry are mostly self-financed and the expected returns are usually sufficient for plantation maintenance (Nawir et al. 2007) but modest (Sunderlin and Huynh 2005). Following a literature review of Sunderlin and Huynh (2005), the major reasons for low returns and incentives of small-scale timber planters are: (1) oversupply and weak demand; (2) too many intermediaries; (3) illegal logging; (4) inadequate knowledge of forest management and the wood market; (5) biophysical disadvantages; (6) policy defiance; and (7) equity problems. The size of plantations under household management usually comprises only some few hectares (Sunderlin and Huynh 2005; Moeliono et al. 2010) and in most cases the wood is sold through middlemen or cooperatives to larger wood processing companies. Smallholders benefit from this in a way that the responsibility of harvest, transport, and selling is organised by these middlemen. For the wood buying companies, the middlemen act as collectors accumulating larger quantities of raw material and help keeping the transaction costs low that would incur when buying small quantities of wood from thousands of households (Moeliono et al. 2010).

Consequently, the households' dependency on middlemen is considerable (Moeliono et al. 2010). The traders have superior knowledge on market prices and they have a market network. In addition, they have also much more experience than the farmers in estimating the growing stock. All that brings the middlemen in

[2] Forestry land in Vietnam is defined as (i) "Land of forest cover" and (ii) "land of no forest cover, planned for afforestation". Consequently, the area of forestry land is with 19.0 Mha higher than the area under forest cover (Clement and Amezaga 2009).

the position of being able to capture a large share of the profits (Nawir et al. 2007; Moeliono et al. 2010), where they do also carry certain risks like mixed quality of timber, price negotiations with many counterparts, interaction with authorities, etc.

There are potential opportunities to improve the negotiation position of smallholders and to possibly increase smallholders' benefits from forest plantations if tools can be developed that allow a rapid estimation of the standing wood volume so that a more objective data base for negotiating the wood value of a plantation is available. Stand density management diagrams (e.g. Barrio-Anta and Álvarez-González 2005) might be such a tool, which in addition add further possibilities like guidance for stand management and silvicultural treatments. The development of the diagrams is straightforward and simple with basic data requirements, and our intention with this paper is to show that on the basis of smallholder plantations in Vietnam, whereas, the approach is general and can be applied elsewhere, too.

Stand Density Management Diagrams

Stand density management or density regulation, is defined as the process of controlling resource competition through manipulation of stand density to reach specific management objectives. That process consists of regulating the number and arrangement of individual trees in a given forest stand through initial spacing and (or) a temporal sequence of thinning events (Newton 1997; Newton et al. 2005). There is a wide range of treatment options and the greatest challenge is to find appropriate levels of growing stock such that the predefined stand characteristics are reached. A common condition is that upper and lower limits of the growing stock must be selected in a way that they result in operational thinning yields: the upper limit is chosen to obtain acceptable stand growth and tree vigor and the lower limit controls acceptable site occupancy (Dean and Baldwin 1996).

The determination of suitable levels of growing stock is a complex process involving biological, technical, and economic factors specific to a particular management situation (Castedo-Dorado et al. 2009). To support the corresponding decisions, science-based methods are required. As one possible method, stand density management diagrams (SDMDs) were proposed as an appropriate silvicultural tool in recent publications (Newton 1997; Newton et al. 2005; Barrio-Anta and Álvarez González 2005; Barrio-Anta et al. 2006; Castedo-Dorado et al. 2009). The use of SDMDs can be considered one of the most effective methods for the design, display and evaluation of different density management regimes in even-aged stands (Jack and Long 1996). In contrast to field trials, stand density management diagrams can quickly be adapted to situations of changing site quality and management objectives, bypassing the restrictions of complex long term experimental plots that are commonly focused to specific site conditions and specific silvicultural objectives. However, it should also be stated that SDMDs cannot replace such kind of experiments and field trials are certainly the best and most reliable way to determine the timing of thinnings and the mentioned limits of growing stock. However, SDMDs offer the possibility of deriving basic stand growth models whenever results are required at short term and limited resources.

Structurally, SDMDs are a set of functional and empirical quantitative relationships, which collectively “illustrate” the cumulative effect of various competition processes on tree and stand yield parameters (Newton et al. 2005). The main axes do usually represent the average size of some basic tree attribute (diameter, height or volume) and stand density. Additional sets of lines are superimposed on the graph and depict: (1) an index relating average tree size to absolute stand density and (2) stand volume, mean diameter or stand height (depending on which is displayed on a major axis).

The objective of this study was to develop SDMDs for pure, even-aged *Acacia hybrid*, *Acacia mangium* and *Eucalyptus urophylla* stands, based on the relative spacing index to characterize growing stock. A basic application of these SDMDs allows simulating different management regimes and supports the smallholder plantation owner in comparing different silvicultural treatments with respect to growth; and this does also include the development of thinning schedules for a wide range of site qualities and management objectives.

Materials and Methods

Data Description

The data used comes from smallholder plantations in four communes of Binh Dinh and Phu Tho provinces, Vietnam. In these communes, three field campaigns in October 2008, September 2009, and March 2010 were done, where a total of 362 sample plots in stands dominated by *Acacia hybrid*, *Acacia mangium*, and *Eucalyptus urophylla* trees were measured. All plots were temporary and their size ranged from 78.5 m^2 to 530.9 m^2 with in average 36 trees per plot. The differences are the consequence of an adaption to local conditions (young stands), it was the aim to have 20–30 trees per plot, and of the establishment of permanent plots with a common size of 10 m in radius for all sites. Re-measurements have not been available in time, so that only the first cycle was used.

During the first two field campaigns, stands and plot locations were selected subjectively based on local knowledge to represent the entire range of ages, stand densities, and sites available in the communes. In 2010, plot locations were objectively selected by superimposing a systematic grid over each commune, and only plots from stands dominated by the species of interest were used to complete the data set. For each tree, the diameter at breast height (DBH, at 1.3 m above ground level) and the species was observed. For measurements of total height a sub-set of trees was chosen with the goal to cover the whole range of the diameter distribution. The height of the remaining trees was estimated, using the stand wise height-diameter relationship as of Eq. 1 (Petterson 1955 as cited in Pretzsch 2009):

$$H_i = 1.3 + \left(\frac{d_i}{a + b \times d_i} \right)^3, \tag{1}$$

where H_i is the total tree height of tree i in m, d_i the diameter at breast height in cm, and a and b are the local coefficients; meaning that plots belonging to a unique stand

were merged together and parameters estimated separately for each stand using ordinary least squares (OLS). Based on this model, single tree volumes over bark, V_i, were predicted from the volume models given in Table 5 in the "Appendix".

Stand stem volume (V , m^3 ha^{-1}), number of stems per hectare (N), and basal area (G, m^2 ha^{-1}) were then derived by plot wise aggregation and extrapolation of single tree values. Additional stand variables calculated are: dominant height (H_d, m, defined as the height obtained from the height-diameter relationship using the diameter derived from the average basal area of the 20% largest trees, e.g. Pretzsch 2009), diameter of trees with average basal area (dg, cm), and relative spacing index (RS, %). A descriptive summary of the data-set is shown in Table 1.

A field plot was taken as single species plot if more than 80% of the trees belonged to that species. Trees of *Acacia hybrid* and *Acacia mangium* can clearly be separated between the northern and the southern research areas. *A. hybrid* occurs only in the Binh Dinh communes (mid-south) and *A. mangium* only in Phu Tho (north). The *Eucalyptus urophylla* data is separated into the southern and northern communes because of differences in climatic conditions, silvicultural management, and plant material (different types of clones).

All stands observed were established by planting with containers. In the case of *Acacia mangium* and *Acacia hybrid* plants were propagated from seeds and cuttings, respectively, and for *Eucalyptus urophylla* plants were grown from tissue culture. Planting densities range from 2 m × 2 m to 3 m × 2 m. The rotation age varies between 4 and 9 years, depending on the financial situation of the households and the purpose of plantations, which in our case is mostly pulp wood production. The latter is also the reason why the application of thinning is uncommon; product size plays no role and thinning is thus unnecessary. Smaller log dimensions are further on easier to handle where access to the plantations is limited, which was partly the case. Except from that, some stands in the database have been thinned, partly for the production of saw wood and partly for extracting fire or construction wood. Information on silviculture of *Acacia mangium* plantations in Indonesia can be found in Krisnawati et al. (2011); which hold in principle for *Acacia hybrid*, too.

Developing a SDMD

Literature references give considerably different formats in presenting SDMDs (Jack and Long 1996). The system that we use here follows the approach that Barrio-Anta and Álvarez González (2005), Barrio-Anta et al. 2006 and Castedo-Dorado et al. (2009) proposed for pedunculate oak, jack pine, or radiata pine stands in Galicia, north-western Spain. As basic components, the relative spacing index and a system of two equations are included: the x-axis is the average height of the 20% largest trees, and the y-axis is the density given as number of stems per hectare in logarithmic scale. Over this basic grid, isolines for relative spacing index, diameter growth and volume development are drawn.

The relative spacing index (see e.g. Clutter et al. 1983 for further references) in percent is given in Eq. 2 and is used to represent the growing stock level. The index is defined as the ratio of the average distance between trees to the dominant height. Assuming the special case for a quadratic spacing, it is:

Table 1 Summary statistics for the field inventory data in Binh Dinh and Phu Tho provinces, Vietnam

Species	Statistic	d_g (cm)	H_d (m)	N_{Plot} (trees per plot)	N (trees per ha)	G (m^2 ha^{-1})	V (m^3 ha^{-1})	RS (%)	t (months)
Acacia hybrid	Min	1.3	2.3	13	909	0.3	0.9	9.9	11
Binh Dinh	Max	14.2	21.1	91	4,456	23	175.3	103	72
$n = 90$	Mean	7.8	12.1	40	2,187	10.9	69.6	24.1	35
	SD	3.1	4.7	22	658	5.7	42.8	18.4	15
Acacia mangium	Min	2.3	2.4	11	508	0.5	0.8	13.6	16
Phu Tho	Max	18.2	23.3	64	2,663	21.6	197.4	116.9	108
$n = 106$	Mean	10.1	12	28	1,256	9.9	61.9	29	49
	SD	3.6	4.2	12	436	5	43	18.3	21
Eucalyptus urophylla	Min	1.2	2	10	884	0.3	0.5	9.5	11
Binh Dinh	Max	13.2	23.4	101	4,456	28.3	209	131	96
$n = 60$	Mean	5.9	8.8	35	2,269	7	39.1	32.2	29
	SD	2.9	4.5	20	701	6.1	46.4	20.5	16
Eucalyptus urophylla	Min	1.7	2.5	10	486	0.2	0.4	11.5	16
Phu Tho	Max	12	18	134	5,857	15.4	116.8	171.1	67
$n = 110$	Mean	6.2	9.9	40	2,603	7.3	39.2	24.8	38
	SD	2.1	3.2	21	1,171	3.5	25.6	17.8	13

n number of plots, d_g diameter of trees with average basal area, H_d average height of 20% largest trees, N_{Plot} number of trees per sample plot, N number of trees per hectare, G basal area per hectare, V volume per hectare, RS Relative Spacing index (quadratic spacing assumed), t age in months, all statistics based on estimations from the given number of plots

$$RS = \frac{100}{\sqrt{N} \times H_d} \times 100, \qquad (2)$$

where H_d is the dominant height and N is the number of trees per hectare. Castedo-Dorado et al. (2009) give several reasons why RS is particularly suited to characterize growing stock levels in SDMDs: (1) it is independent on stand age (except for very young stands) and site quality; (2) dominant height is, from a biological point of view, the best index for establishing thinning intervals; (3) the linkage between dominant height growth and forest production adds further utility to these diagrams for forest management purposes; and (4) it is commonly used to control density in intensively managed plantations.

A further component of the diagram is the diameter development, expressed here as the diameter of trees with average basal area d_g. This diameter development can be modeled as in Eq. 3. It is based on the relationship between average tree size, density N, and dominant height H_d that characterizes stand productivity (e.g. Long and Shaw 2005):

$$d_g = b_0 N^{b_1} H_d^{b_2} \qquad (3)$$

The current stand volume (V) results then from the volume of one average tree (modeled from the diameter of trees with average basal area and dominant height) and the number N of trees per hectare (e.g. McCarter and Long 1986).

$$V = b_3 d_g^{b_4} H_d^{b_5} N^{b_6} \qquad (4)$$

Equations 3 and 4 together define a structurally simultaneous system of equations, where N and H_d are the exogenous variables (totally independent from the system); d_g and V are the endogenous variables (intended to explain); and d_g is the endogenous instrumental variable (also appears on the right hand side of other equations). The coefficients are given by $b_0 - b_6$. To fit the two equations simultaneously, the full information maximum likelihood (FIML) technique was applied using the MODEL procedure of SAS/ETS (SAS Institute Inc. 2008a).

For a graphical representation of the model, it is necessary to solve Eqs. 2–4 for the dependent variable N in the diagram. The result for the relative spacing index is given in Eq. 5.

$$N = \frac{10{,}000^2}{RS^2 H_d^2} \qquad (5)$$

By keeping RS constant and solving the equation through the range of H_d covered in the data set, it is possible to derive multiple isolines. Isolines for the diameter of trees with average basal area were calculated in a similar way, by setting d_g constant and solving Eq. 3 for N with the same values for H_d as above:

$$N = \left(\frac{d_g}{b_0 H_d^{b_2}} \right)^{1/b_1} \qquad (6)$$

For the isolines representing stand volume, Eq. 3 must first be substituted into Eq. 4 and then solved for N with a set of dominant stand heights:

$$N = \left(\frac{V}{b_3 b_0^{b4} H_d^{b_2 b_4 + b_5}} \right)^{1/(b_1 b_4 + b_6)} \tag{7}$$

For the variables RS, d_g and V, the observed minimum and maximum values from the stand data were used so that the set of isolines mirrors fundamental stand characteristics of exactly these stands.

Model Validation

For validating the SDMD model formed by Eqs. 3 and 4, we applied leave-one-out cross validation to the data sets described in Table 1. From each data set one observation was set aside for validation and the rest was used for model fitting. From the values of the left-out set of observations, diameter of trees with average basal area and volume per hectare were calculated using the corresponding parameter estimates, resulting in one prediction from data that was not used for parameter estimation. Having n observations in a data set of a certain species, the procedure was repeated n times; so that each observation set was used once for validation. Finally, the resulting n predicted values of diameter of trees with average basal area and volume per hectare (Y_{pred}) and their observed counterparts (Y_{obs}) were used for calculating cross-validated statistics of bias, root mean square error ($RMSE$), and coefficient of determination (R^2).

$$Bias = \frac{\sum \left(Y_{obs} - Y_{pred} \right)}{n}$$

$$RMSE = \frac{\sqrt{\sum \left(Y_{obs} - Y_{pred} \right)^2}}{\sqrt{n - p}}$$

$$R^2 = 1 - \frac{\sum \left(Y_{obs} - Y_{pred} \right)^2}{\sum \left(Y_{obs} - \bar{Y}_{obs} \right)^2}$$

Site Index Models

The SDMDs are applied here to even-aged young plantation forests and age does not enter as an input variable. If age is to be integrated into the diagrams, we need models relating dominant stand height values—on which the diagrams are based—to age. In our case where only temporary data is available the guide curve technique for model development was applied. As guide curve, a modification of the model proposed by Hossfeld (cited in Peschel 1938) was used:

$$H_d = \left(\frac{t}{a + b \times t} \right)^3, \tag{8}$$

where H_d is the dominant stand height and t the age in months. The model coefficients are a and b, where b is related to the horizontal asymptote of the curve, which is at the ordinate value of $1/b^3$. This allows fitting a polymorphic family of

curves with different asymptotes. The constraint is that this model should only be used with fast growing tree species, which is the case here. The fitting of the parameters to the data was done with the NLIN procedure of SAS/STAT (SAS Institute Inc. 2008b). After the guide curve had been determined, it becomes necessary to develop a family of curves which should cover the whole range of variation in the data set for site quality estimation. For these site index curves a reference age has to be defined. The average stand height at this reference age can then be used as an index of stand productivity (site index). Usually the reference age is set close to the rotation age. Here, for the short rotation smallholder plantations—in a relatively arbitrary manner—an age of 4 years was defined.

The next step is to define the number of curves that are to be depicted graphically. The expected average stand height at reference age gives an indication which values to use. Eventually, the curves are to cover the entire range of values observed in the field.

In a last step, the model coefficients must be determined so that all single curves are forced through the defined values of site index. This is done by maintaining coefficient a and modifying b, where the latter defines the asymptote. The following example shows the calculations of a site index curve for 8 m at a reference age of 48 months for *Acacia mangium* (a was previously estimated at 4.6806 when the guide curve was fitted):

$$8 = \left(\frac{48}{4.6806 + b \times 48}\right)^3 \rightarrow b = \left(\frac{1}{8^{1/3}} - \frac{4.6806}{48}\right) = 0.4025,$$

and the resulting site curve predicting the average height $H_{SI=8}$ at age t given site index $SI = 8$ is

$$H_{SI=8} = \left(\frac{t}{4.6806 + 0.4025 \times t}\right)^3.$$

To estimate the site index from known values of dominant height and age, a special form of Eq. 8 has to be derived. To do this, t_{SI} is defined as the reference age and set equal to t. Then, H_d must be equal to the site index, so that

$$b = \left(\frac{1}{SI^{1/3}} - \frac{a}{t_{SI}}\right). \tag{9}$$

By substituting into Eq. 8 we get

$$H_d = \frac{1}{\left(\frac{1}{SI^{1/3}} - \frac{a}{t_{SI}} + \frac{a}{t}\right)^3} \tag{10}$$

which is the model to predict dominant height at any age for a given site index, or

$$SI = \frac{1}{\left(\frac{1}{H_d^{1/3}} - \frac{a}{t} + \frac{a}{t_{SI}}\right)^3} \tag{11}$$

to estimate the site index of a given stand when dominant height and age are known.

Results

Stand Density Management Diagrams for Three Exotic Tree Species in Vietnam

The statistics from the cross validation of Eqs. 3 and 4 are shown in Table 2. The parameter estimates in Table 3 are obtained from fitting the complete data set, and the corresponding *P* values indicate whether they are estimated to be significantly different from zero or not ($\alpha = 0.05$). All the equations performed well and explained between 81% and 99% of the total variability for diameter of trees with average basal area and total stand volume. The bias of the two components of the equation system can be considered to be negligible across all species, especially when compared to the average values of Table 1. The root mean square errors are usually not higher than 15% of the average of the corresponding observed variable, except for *Eucalyptus urophylla* in the southern communes, showing a value of 21.1% for the diameter equation. This might be explained by the lower sample size or by a greater variety of stand characteristics due to storm damages, different clones, or silvicultural treatments. In general it can be said that the fit statistics for volume estimation are far better than the ones for predicting diameter of trees with average basal area.

For some of the coefficients, the null hypothesis could not be rejected, as is the case for the *Eucalyptus urophylla* data set in the southern communes; the one showing the worst fit statistics. As the regressors are not combined by linear terms, a zero value will invalidate the complete model. This can be seen as a general problem for such kind of models; in the present case, however, we may assume that it is an effect of too small sample size. Therefore, all coefficient estimates were further used, disregarding their estimated significance.

An example for a SDMD is shown in Fig. 1 for *Acacia mangium*; the ones for the other species are similar in principle and not explicitly given here. The x-axis is dominant height and the number of stems per hectare is on the y-axis in logarithmic scale. The dominant height values for the *Acacia mangium* model range from 4 m to

Table 2 Goodness-of-fit statistics for fitting the system of two equations with the full information maximum likelihood technique. Bias, relative root mean squared error, and coefficient of determination are calculated using leave-one-out cross validation (RMSE% is the RMSE in relation to the average of the observed values)

Province	Species	Eqs.	*df*	Bias	RMSE%	R^2
Binh Dinh	*Acacia hybrid*	3	87	−0.042	12	0.91
		4	86	0.119	5.2	0.993
	Eucalyptus urophylla	3	57	−0.031	21.6	0.813
		4	56	−0.053	8.1	0.996
Phu Tho	*Acacia mangium*	3	103	−0.033	14.6	0.835
		4	102	0.114	5.8	0.993
	Eucalyptus urophylla	3	107	0.009	15.1	0.812
		4	106	−0.041	4	0.996

Table 3 Non-linear regression coefficients obtained by simultaneously fitting the system of two equations predicting diameter of trees with average basal area (dg) and stand volume (V) using the full set of observations. The level of significance is $\alpha = 0.05$

Eqs.	Parameter	Binh Dinh				Phu Tho			
		Acacia hybrid		*Eucalyptus urophylla*		*Acacia mangium*		*Eucalyptus urophylla*	
		Estimate	*P* value	Estimate	*P* value	Estimate	*P* value	Estimate	*P* value
3	b_0	9.085	0.0058	2.038	0.1141	6.031	0.0144	6.564	0.0005
	b_1	−0.275	<0.0001	−0.096	0.2414	−0.199	<0.0001	−0.236	<0.0001
	b_2	0.787	<0.0001	0.836	<0.0001	0.776	<0.0001	0.771	<0.0001
4	b_3	0.000075	0.0163	0.000075	<0.0001	0.00004	<0.0001	0.000058	<0.0001
	b_4	2.117	<0.0001	1.992	<0.0001	1.882	<0.0001	2.137	<0.0001
	b_5	0.641	<0.0001	0.769	<0.0001	0.973	<0.0001	0.658	<0.0001
	b_6	0.993	<0.0001	0.985	<0.0001	1.035	<0.0001	1.019	<0.0001

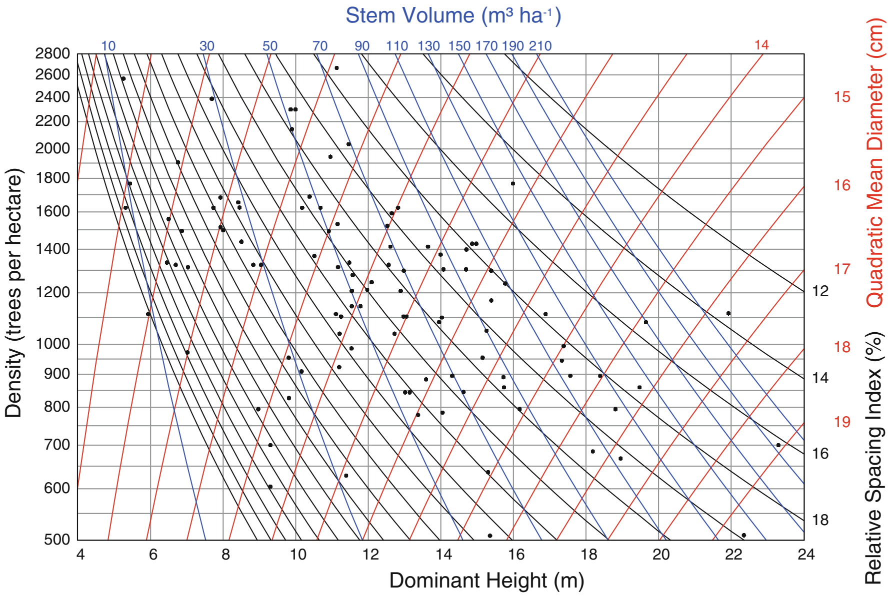

Fig. 1 Stand density management diagram for *Acacia mangium* in Ca Dinh and Tram Than commune, Phu Tho province, Vietnam. Isolines for relative spacing index and stem volume slope *downward* from *upper left* to *lower right*, with a steeper decline for volume. Fixed values for diameter of trees with average basal area (Quadratic Mean Diameter) are depicted with *lines* running *upward* sloped from *lower left* to u*pper right*. The *black dots* represent the field data used to fit the model. A simplification of the rather complicated diagram is possible by showing only one part of the model, for example volume

24 m. Very young stands with values around 2 m in dominant height are left out because their *RS* values become very large and the corresponding values for volume per hectare are negligibly small. The 106 *Acacia mangium* stands used to build the diagram had densities from 500 trees per hectare to 2,700 trees per hectare.

The relative spacing index isolines are drawn in black color and slope downward from left to right. For *Acacia mangium*, the uppermost line corresponds to a value of 12%, it is assumed that this value reasonably approximates the maximum size-density relationship for the particular species and thus represents the maximum combination of dominant height and number of stems per hectare possible in stands of this species in the studied communes. Additional lines range up to an average tree to tree distance of 50% of dominant height. Constant values for diameter of trees with average basal area are depicted with red lines running upward sloped from left to right. They are highly sensitive to stand density and range here from 4 cm to 19 cm. Total stand stem volume values range from 10 m^3 ha^{-1} to 210 m^3 ha^{-1} and the blue isolines slope downward from left to right, in accordance with the principle that stand productivity is highly influenced by height development.

The black dots in Fig. 1 are the field measured data, illustrating the range of applicability of the model. It is interesting to note that corresponding values for diameter of trees with average basal area and volume per hectare do not necessarily fit the ones observed in the field; in the diagram the model estimates based on stand

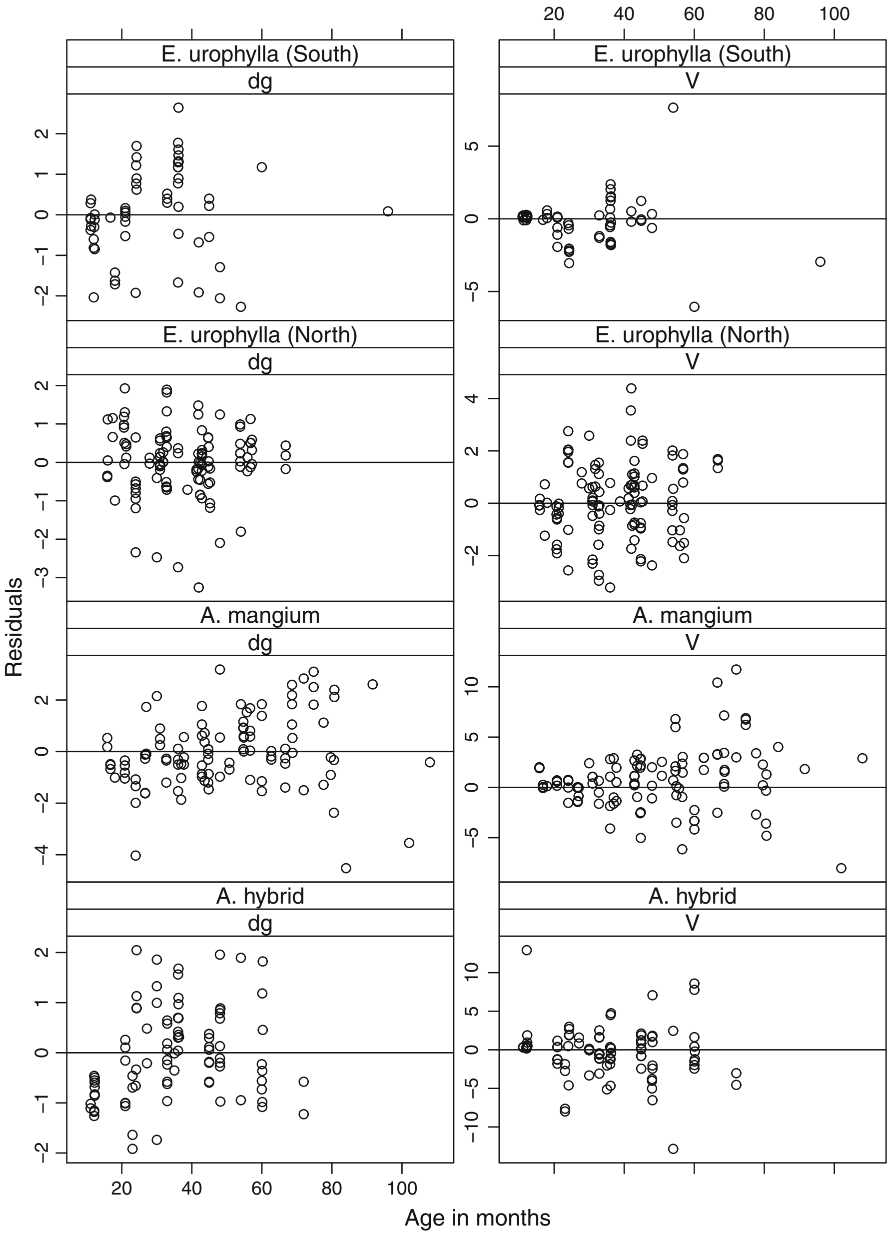

Fig. 2 Plots showing the residuals for the diameter (Eq. 3, dg) and volume (Eq. 4, V) equation in dependency of the age of the stands

density and dominant stand height are shown. E.g. the rightmost point with a stand density of 700 trees per hectare and a dominant height of 23.3 m has an observed diameter of trees with average basal area of 15.3 cm and an observed volume of 120 m^3 ha^{-1}. The modeled diameter lies between 18 cm and 19 cm and the modeled

Table 4 Parameters for the guide curves used to derive site index models. *df* are the degrees of freedom, Root-MSE is the standard error and the parameters estimates of Eq. 8 are given by *a* and *b*

Province	Species	*df*	Root-MSE	*a*	*b*
Binh Dinh	*A. hybrid*	86	4.914	3.241	0.334
	E. urophylla	55	5.857	4.201	0.327
Phu Tho	*A. mangium*	105	4.566	4.681	0.333
	E. urophylla	108	6.325	2.953	0.381

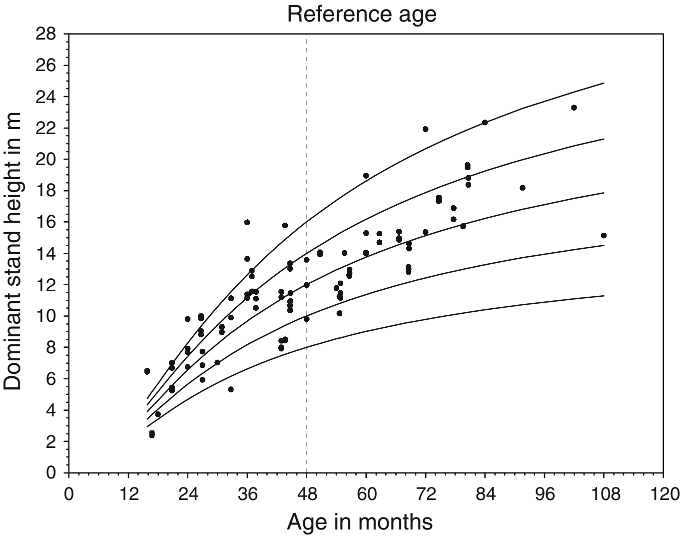

Fig. 3 Family of curves for the relationship between dominant stand height and stand age for *Acacia mangium* in Ca Dinh and Tram Than commune, Phu Tho province, Vietnam

volume between 190 m^3 ha^{-1} and 210 m^3 ha^{-1}. This is a rather large deviation from the observed values and might indicate a model weakness when it comes to estimate greater values. This has been further investigated in Fig. 2, which plots the residuals of the two parts of the model (Eqs. 3 and 4) against the age of the plantations for all four cases, assuming that generally greater values are observed in older stands. For *Acacia mangium* a clear increase of the errors with increasing age can be observed for both, diameter and volume estimation. The correlation between the two is with 0.76 rather high, meaning that a high error in diameter estimation causes a high error in volume estimation. For the other cases the diameter and volume residuals are rather evenly distributed.

Site Index Models

The estimated coefficients and the goodness of fit statistics for the four guide curves are given in Table 4. The two models for *Eucalyptus urophylla* show higher errors

than for the other two species because of higher variability in these datasets, mainly due to differences in clones and stand management. In Fig. 3 the resulting family of curves together with the plot observations of dominant height and age are depicted. The given site indexes are the dominant height values which the respective curve would reach at the reference age; which was set to 4 years for all species.

Because of the absence of data from suitable permanent observation plots, the curves presented here come from temporary observation plots. This lack of re-measured data implies that the guide curve technique may carry a considerable bias, as it is assumed that in the data all combinations of site quality and age are equally distributed. It may result then, that more productive sites reach the harvest dimension/volume earlier and are, therefore, underrepresented in the older age classes, so that a possible bias away from the true average height growth trend may result (Clutter et al. 1983; Walters et al. 1989).

Discussion and Conclusions

Within the here presented framework of SDMDs, two factors are determining the thinning schedule: the target stand dimension at rotation age and the upper and lower growing stock limits (Barrio-Anta and Álvarez-González 2005; Barrio-Anta et al. 2006). The target stand dimension can be defined by any reasonable combination of two of the following variables: dominant height, diameter of trees with average basal area, number of stems per hectare and total stand stem volume depending on the final objectives of the stand management.

For the second factor, it must be considered that the two aspects of growth—stand versus individual—cannot be maximized simultaneously. The selection of upper and lower growing stock limits represents a compromise between volume production on an area basis and single tree growth and size, which is a direct consequence of management objectives (Long 1985). To define appropriate upper and lower growing stock limits, *RS* values must be defined that avoid density related mortality and maintain adequate site occupancy, respectively (Castedo-Dorado et al. 2009).

Thinning intervals can be determined between these limits, where the lower limit is set to a constant value of relative spacing index somewhat above canopy closure. Another approach is to define thinning intervals in terms of height growth in combination with an upper growing stock limit, or with a thinning weight defined as an increment of the relative spacing index value that guarantees stand stability after thinning (see also Barrio-Anta and Álvarez-González 2005).

Apart from developing thinning schedules, which is their main application, SDMDs can also be used for estimating certain stand characteristics, such as growing stock, and for illustrating fundamental characteristics of stand growth. Once a diagram is produced, any known combination of two variables included in the diagram, directly gives the remaining ones. Thus, standing wood volume, for example, could be assessed using tree density and dominant height as entry variables. These two can easily be measured with very basic inventory equipment

such as ropes of fixed length for density estimation based on fixed area plots, and telescope bars for tree height measurements.

The SDMD approach as applied here is subject to two restrictions: at first, we assume no mortality during stand development; if the upper and lower stocking limits are selected in a way that natural mortality is unlikely, this assumption is reasonable. Density independent mortality like lightning strikes, wind damage, fire, insect pests, etc. is still not covered. A similar assumption can also be found in SDMDs constructed for other species using partially different size-density indexes (e.g. McCarter and Long 1986; Barrio-Anta et al. 2006; Castedo-Dorado et al. 2009). A possible solution is to implement a mortality model into the presentation of the SDMD like Castedo-Dorado et al. (2009) did for radiata pine stands in north-western Spain. Then, however, data from permanent sample plots is required, which was not available here.

The second assumption is that a thinning from below has no influence on the dominant height. This can be seen as realistic, as in low thinnings dominant trees are not removed. Another assumption concerns the estimation of site quality mentioned under 3.2, when only temporary plots are used, so that possibly older age classes are underrepresented. With respect to site quality estimation it is also important to have good information about the age of the plantations. In our case we asked farmers directly, which can be problematic if false information is provided. Verification by the use of bore cores applied to a sub-sample of trees is thus recommended.

As shown in Fig. 2, the *Acacia mangium* model shows a clear weakness in estimating larger values of diameter and volume. A large diameter error is thereby causing a disproportionally high volume error as the diameter is nearly squared in Eq. 4. The reason lies in an incorrect estimation of the size density relationship caused from an underrepresentation of the oldest age classes in that data set. Stands of that age classes have always been thinned in the past, whereas the younger age classes have not and the trend from the younger classes does consequently not fit very well to the older ones. A consequence of this observation is that all age classes and silvicultural treatments should be evenly distributed in the data set.

Concerning volume estimation, the underlying methods do not rely on own studies capturing the local conditions. Instead, as in many practical forest inventory situations, we needed to resort to models that originated as closely as possible to the research areas.

The summary Table 1 clearly shows that the range of age classes in the study communes is restricted. Plantations are mainly planted for pulp wood production that generate short term income for the smallholder; stands with rotation lengths of more than six, sometimes even 5 years, are hard to find or are simply not existent. As a consequence, from a methodological point of view, the developed models are only valid for the ranges given in Table 1.

The use of SDMDs is largely limited to evaluating density management outcomes in terms of mean tree size and volumetric yields. For pulp wood production, this may be fully sufficient. However, if the management goal is to maximize overall value, an estimate of the underlying diameter distribution is required that gives the inherent relationship between monetary value and tree size (Newton et al. 2005). For the development of structurally complex stands (i.e. mixed stands, natural regeneration),

SDMDs are too simple to help in deriving management plans (Valbuena et al. 2008); in these more complex systems, more complex models are needed.

The SDMD approach is an immediately operational tool with a wide potential of use for forest managers and landowners. The primary goal is to derive alternative thinning regimes, which can be done relatively fast and easy. The graphical presentation allows the direct reading of stand values like volume, diameter of trees with average basal area and relative spacing index for any combination of height and density values. In case of the latter application scenario, the rather complicated appearance of the diagrams could be reduced by showing only one part of the model; for example volume isolines on top of isolines for height and density. Any kind of further information can also be added, as long as it is correlated to the number of stems per hectare and dominant height. This could for example be: (1) carbon stock, which is important to achieve for CDM projects (Barrio-Anta et al. 2006); (2) assessment of stand stability (Castedo-Dorado et al. 2009; López-Sánchez and Rodríguez-Soalleiro 2009); (3) non timber forest products; (4) habitat requirement for wildlife species; or (5) merchantable stand volume with given merchantable diameters (Castedo-Dorado et al. 2009). The data required for the equations and diagrams is usually available from common forest inventories.

A practical advantage of the model is that there is no need for a forest growth simulator to obtain outputs and no iterative method must be used to derive thinning schedules to reach specific targets (Castedo-Dorado et al. 2009). Of course, these models cannot compete with dynamic stand growth models, because these provide a more detailed yield analysis, which the SDMD is not able to do. However, for everyday management tasks and in the absence of a suitable information base (that is, when there is a lack of permanent data, of computing capacity and of knowledge), SDMDs are useful in a complementary way and offer a possibility to gain immediate insight into basic planning approaches in forest management.

Further on, the basic data requirements allow including local people such as the plantation owners in the inventory work, as we did, and by that give them training in measuring stand characteristics necessary for using the SDMD. The development of the diagrams and the teaching of their application could be done by local forestry authorities. However, in our case we did not applied the described approach in practice and we understand it more as a case study to promote the use of SDMDs in small scale forestry applications.

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Conflict of interest The authors declare that they have no conflict of interest.

Appendix

For the estimation of single tree volumes the models given in Table 5 have been used, where V_i gives the single tree volume in m^3 of a tree i and the other variables are as defined earlier. The term X was used in the given publication to transform from underbark to overbark volume.

Table 5 Models used for the estimation of single tree volumes. d_i is the diameter at breast height and H_i is the total height of a tree i

Species	Model	Units	Source
Acacia hybrid	$V_i = \frac{10^{-4}\frac{\pi}{4}d_i^2 H_i \times 0.945}{X}$	d_i in cm, H_i in m	MARD (2003), p. 54
Acacia mangium	$V_i = 0.000071 d_i^{1.7408} H_i^{1.0187}$	d_i in cm, H_i in m	MARD (2001), p. 54
Eucalyptus urophylla	$V_i = 03256(d_i^2 H_i)^{0.9106}$	d_i in m, H_i in m	MARD (2001), p. 24

$$X = 2.38\left(\frac{H_i-1.3}{H_i}\right) - 5.47\left(\frac{H_i-1.3}{H_i}\right)^2 + 12.9\left(\frac{H_i-1.3}{H_i}\right)^3 - 15.25\left(\frac{H_i-1.3}{H_i}\right)^4 + 6.59\left(\frac{H_i-1.3}{H_i}\right)^5$$

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